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Zuilichem, D.J. van; Stolp, W.; Janssen, L.P.B.M.

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Engineering Aspects of Single- and Twin-screw Extrusion-cooking of Biopolymers*

D.J. van Zuilichem, W. Stolp,

Department of Process Engineering, Agricultural University, 6703 BC Wageningen,
De Dreijen 12, The Netherlands

and

L.P.B.M. Janssen,

Laboratory for Physical Technology, Delft University of Technology,
2628 BW Delft, Prins Bernhardlaan 2, The Netherlands

ABSTRACT

A survey is given of the properties of single- and twin-screw extruders. The influence on the design of the different leakage gaps existing in co-rotating, counter-rotating, self-wiping, twin-screw extruders and single-screw equipment is discussed. The mixing effects in single- and twin-screw equipment and the shear distribution and shear levels that can be generated in the equipment are discussed. The overheating effect possible in single-screw extruders is related to the type of flow in the extruder channel. Finally, the properties and power consumption of Cincinnati conical, twin-screw extruders are discussed.

INTRODUCTION

When considering the cooking-extrusion of foods and feeds, a distinction can be made between single-screw extruders (s.s.e.'s) and twin-screw extruders (t.s.e.'s), the main difference being in the conveying mechanism (see Table 1). In the s.s.e. the conveying action is the result of two friction effects: first the friction between screw and product and second the friction between barrel and product. The s.s.e. *needs* the barrel wall for a good conveying action and the barrel wall will be an

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TABLE 1
Main Differences Between Single- and Twin-screw Extruders

	<i>Single-screw extruder</i>	<i>Twin-screw extruder</i>
Main energy supply	Viscous dissipation	Heat transfer to barrel
Transport mechanism	Friction between metal and food material	Positive displacement
Throughput capacity	Dependent on moisture- and fat-content and pressure	Independent
Approximate specific power consumption per kg product	900-1500 kJ kg ⁻¹	400-600 kJ kg ⁻¹
Heat distribution	Large temperature differences	Small temperature differences
Mechanical power dissipation	Large shear forces	Small shear forces
Degassing possibilities	Simple	Difficult
Rigidity	High	Bearing construction is vulnerable
Capital costs	Low	High
Minimum water content	10%	8%
Maximum water content	30%	95%

important part of the design. In a t.s.e. with closely intermeshing screws the product is enclosed between screws and barrel in C-shaped chambers (see Fig. 1), is therefore prevented from rotation with the screws, and so is conveyed positively towards the die. Here, depending on process conditions, friction at the barrel wall is less important. However, the screw geometry itself is important, as it is now possible to influence the pressure built up in the chambers and the resulting leakage flow back from one chamber to the previous one or across to the neighbouring screw.

An s.s.e. can be compared to and modelled as a continuous channel with a pseudo fully-developed flow profile and accompanying temperature profile. This is in contrast with the conditions in a closely-

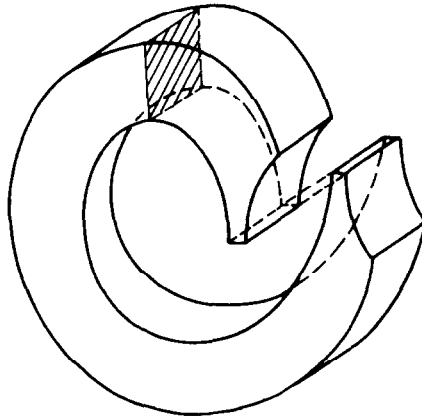


Fig. 1. C-shaped chamber of twin-screw extruder.

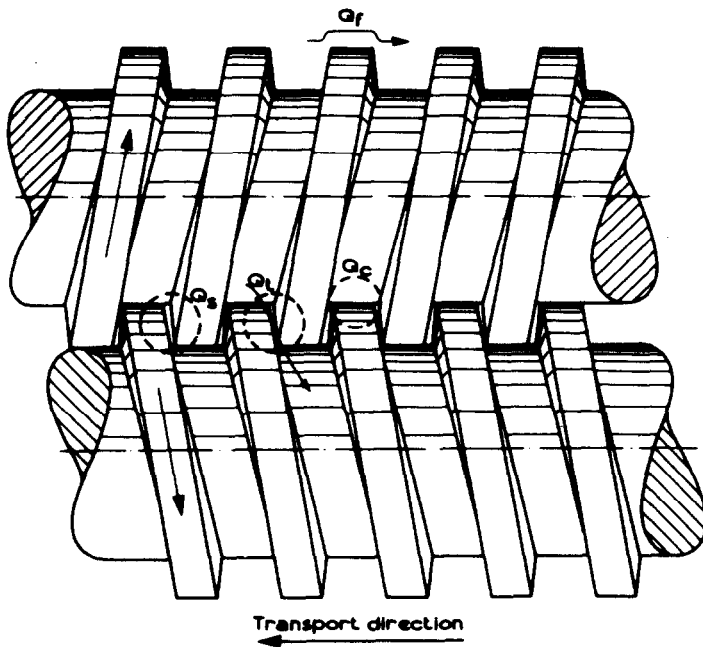


Fig. 2. Leakage flows in a closely-intermeshing, counter-rotating twin-screw extruder.

intermeshing t.s.e. forming closed C-shaped chambers so that no fully-developed profiles can be present. Design requirements and shear limitations mean that t.s.e.'s are never fully sealed, and that there is a certain interconnection between the chambers resulting in a certain leakage flow (see Fig. 2) which can be small, as in the small gaps of the pumping zone in counter-rotating extruders, or can be considerable in the wide gaps of a self-wiping co-rotating t.s.e. (see Figs 3, 4, 5 and 6). Such an extruder can also be described using the model of a pseudo-continuous channel with large ducts; so too can non-intermeshing screw combinations where clear continuous channels exist along the whole length of the extruder as with the s.s.e. There will remain the difference of incompletely-developed flow and temperature profiles.

If a classification of extruders is required, then it is logical to introduce a distinction based on the 'openness' of the channel, or the restrictions limiting continuous action. In intermeshing t.s.e.'s, the action is governed by positive displacement with leakage, the drag flow and the pressure flow being considered as secondary effects.

Self-wiping t.s.e.'s can be regarded as a special, intermediate, case. Although the intermeshing region forms a barrier for backflow and

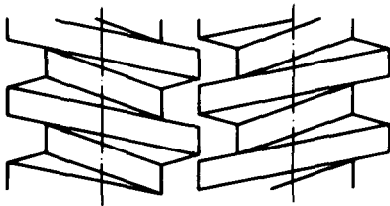


Fig. 3. Example of twin-screw extruder: non-intermeshing.

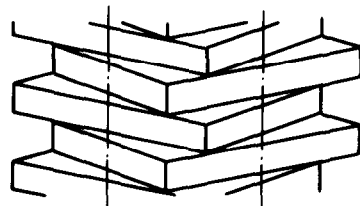


Fig. 4. Example of twin-screw extruder: intermeshing counter-rotating.

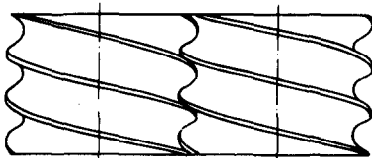


Fig. 5. Example of twin-screw extruder: self-wiping.

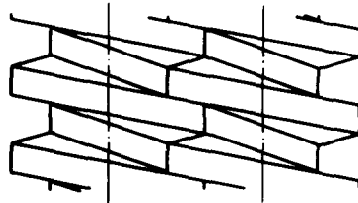


Fig. 6. Example of twin-screw extruder: intermeshing co-rotating.

produces a positive displacement action, because of the openness of the channel, the balance between drag flow and pressure flow largely determines the transport.

CO-ROTATING VERSUS COUNTER-ROTATING TWIN SCREW EXTRUDERS

Conclusion A: leakage gap design

Although the mechanism of transportation in co-rotating and counter-rotating, closely-intermeshing t.s.e.'s is similar, there are some differences in their flow fields and mixing effects. Pressure is built up in the tangential direction around the C-shaped chambers. With counter-rotating screws, there tends to be a build up of pressure on the converging side of the screws while on the diverging side there is a low pressure region (Figs 7 and 9(a)). This pressure difference in the screw chambers mainly influences the leakage through the calender gap in question and through the side gap. On the other hand, with co-rotating screws it can be concluded that the tangential pressure build up influences the leakage through the tetrahedron gap most (see Figs 7 and 9(b)). Further, the drag component of the leakage flows favours the calender gap and side gap most in counter-rotating machines, whereas in co-rotating extruders the resultant of the drag flow will be mainly through the tetrahedron gap. From geometrical considerations (the screws must fit into each other) the tetrahedron gap must be designed much bigger in size in co-rotating than in counter-rotating twins. This can be seen qualitatively in Fig. 8, where cross-sections in the mid-plane between and parallel to the screw axes are drawn for typical counter-rotating and co-rotating screws.

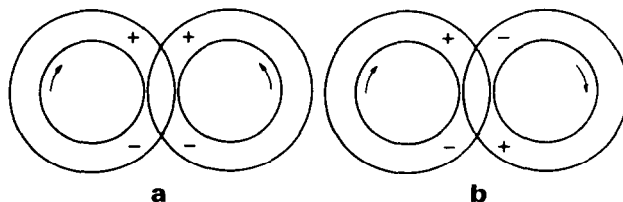


Fig. 7. Pressure distribution in twin-screw extruders. (a) Counter-rotating; (b) co-rotating.

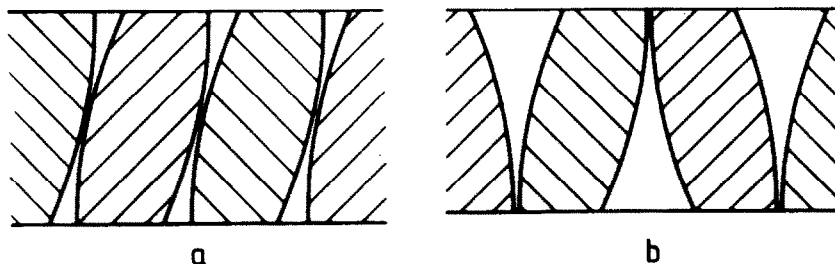


Fig. 8. Cross-section of the screws at the intermeshing part. (a) Counter-rotating; (b) co-rotating.

Conclusion B: mixing

All the above factors favour flow through the tetrahedron gap in co-rotating systems. Since the tetrahedron gap is the only gap that connects the chambers associated with one screw with those formed by the other, it is clear that in co-rotating extruders the material from the one screw mixes fairly well with that from the other screw. In counter-rotating systems, however, the mixing of the material carried by the two individual screws is much less, but the positive displacement action is greater. The self-wiping, co-rotating t.s.e., as shown in Fig. 5, forms an extreme case. Here all the gaps are minimised except for the tetrahedron gap. The material flows very easily from one screw to the other, thus ensuring good mixing between the material carried by the two screws – at the cost of positive displacement action. The only restriction to back flow is the ‘kink’ that is formed in the channel, no relevant intermeshing in the channel direction being present.

SHEAR DISTRIBUTION IN VARIOUS EXTRUDERS

Shear is an important consideration in the choice of an extruder. Some food materials have to be handled gently and low shear levels are required. Other materials may demand high shear for the whole processing period or need a high shear treatment for a short time. Depending on the application then, minimum, maximum or average shear rates may exist which are necessary for the achievement of particular process goals. The maximum shear rate in an extruder will usually be achieved

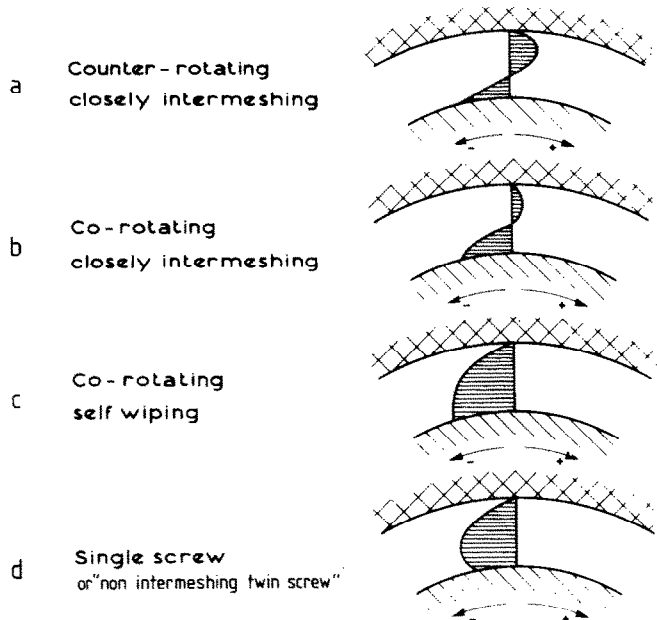


Fig. 9. Flow profiles in different extruder types.

in the flow through one of the leakage gaps: in a single-screw extruder this will of course be the flight gap; in twin-screw machines there are more gaps. In both cases, however, the quantity of material leaking through the flight gap is small, and the effects of this mechanical working on the bulk of the product is usually slight, except in so far as it may be important in the melting region.

In order to compare the average shear in various types of extruders, the positive displacement action should be considered. Figure 9(a) shows that closely-intermeshing, counter-rotating t.s.e.'s have virtually no net back leakage in the channel, which means that the positive displacement efficiency is very high. In closely-intermeshing, co-rotating t.s.e.'s (Fig. 9(b)) the leakage gaps are larger, thus diminishing the positive displacement action. This is even more so in self-wiping, co-rotating t.s.e.'s (Fig. 9(c)). In the case of s.s.e.'s (Fig. 9(d)) the positive conveying action with a given back pressure is very small because of the unrestricted continuous channel. Since, in general, the channel depth at comparable screw diameters also decreases when going from closely-

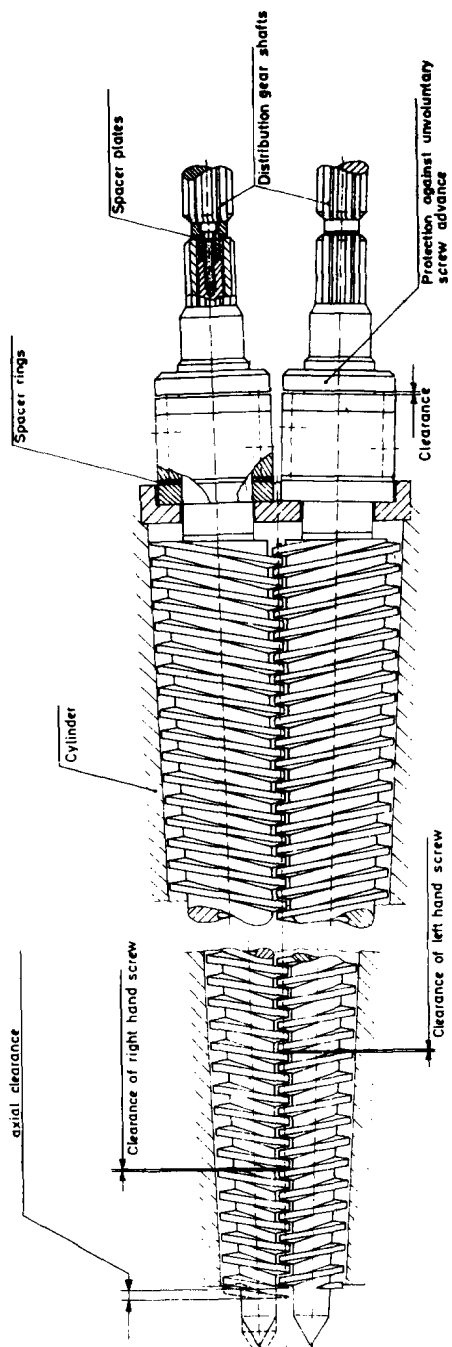


Fig. 10. Example of a screw-set for a conical counter-rotating twin-screw extruder (Cincinnati).

intermeshing to single-screw extruders it is obvious that for comparable output rates both single-screw extruders and self-wiping extruders must operate at much higher rotational speeds than closely-intermeshing, co-rotating and counter-rotating machines. Because of the wider clearances, which are related to the smaller positive displacement action, high rotation speeds can be more easily achieved in self-wiping, twin-screw and in single-screw extruders than in closely intermeshing twin-screw extruders. It can now be concluded from the relationship between rotational speed requirements and the relative channel and chamber depths that the average shear rates will be highest in single-screw extruders, and will be successively lower with the self-wiping, the closely-intermeshing, co-rotating and closely-intermeshing, counter-rotating geometries.

As stated above, the greatest shear levels in the extruder will occur in the various leakage gaps. In single-screw and self-wiping extruders all channels are large except for the flight gap and the maximum shear rate will be of the same magnitude as the average. This is not true for closely-intermeshing extruders. In co-rotating, closely-intermeshing machines a special shear region is present in the tetrahedron gap. The shear in this gap, however, is not very large since the walls of this gap move in essentially the same direction. Although an extremely high shear can be experienced in the calender gap this is not usually significant since virtually no material will be transported through this gap (see

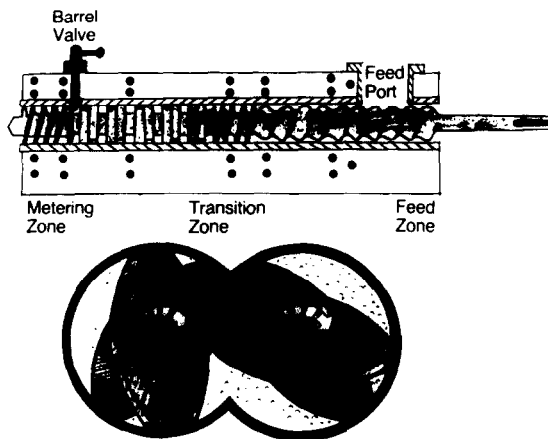


Fig. 11. Cross-section of a twin-screw extruder with barrel-valve (Baker Perkins).

Fig. 2). In counter-rotating, closely-intermeshing extruders the calender gap plays an important role. Material transported through this gap will experience high shear and elongational forces, thus giving high micro-mixing and dispersion. Since during normal operating conditions in counter-rotating extruders with reasonable calender gaps most of the material will pass this gap at least once it can be concluded that in counter-rotating extruders the average shear level is very low but a short-time, high-shear treatment is also present. Shear increase can be achieved by designing a conical housing and screw combination with a suitably-designed throttle zone as in the Cincinnati design or 'barrel-valve' as in the Baker Perkins design (Figs 10 and 11).

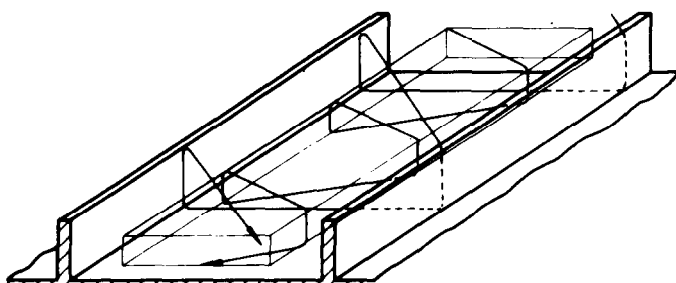


Fig. 12. Flow pattern in the channel of a single-screw extruder.



Fig. 13. Recirculation in the chamber of a twin-screw extruder.

MIXING AND HEAT TRANSFER

In an s.s.e. the flow field can be calculated easily from a judicious combination of cross-sectional and down-channel velocity profiles, to give a helical flow as indicated in Fig. 12. In this flow field the trajectory of a liquid particle is completely determined by the height at which

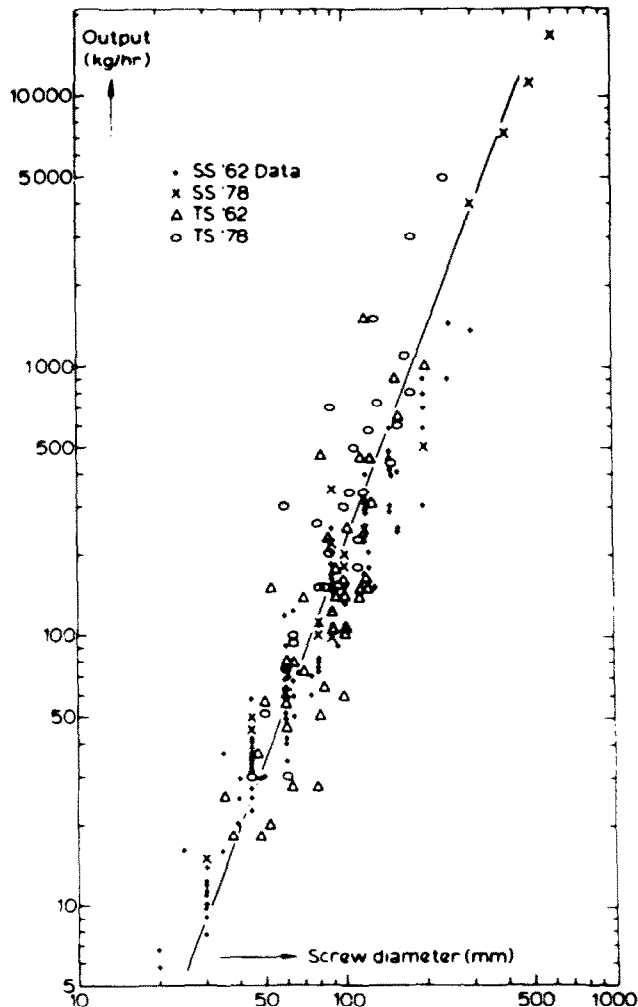


Fig. 14. Throughput of different extruder types according to supplier specifications.

it enters the channel in the fully-filled pumping zone. However, particles that enter this zone near the centre of the helical flow field will never approach the wall, and because of the poor thermal conductivity of some biopolymers heat generated by viscous dissipation in this region is only slowly removed by conduction to the wall. This can result in high temperatures along the middle of the channel.

Conclusion C: heat transfer

The situation in closely-intermeshing t.s.e.'s is different, as the material is redistributed near the intermeshing region. Material coming from the inner part of the helical flow field is transferred to the outer part near the wall (Fig. 13), thus ameliorating heat transfer. Since t.s.e.'s also have lower rotational speeds in general, with less energy dissipation, this ensures a good thermal homogeneity in the product.

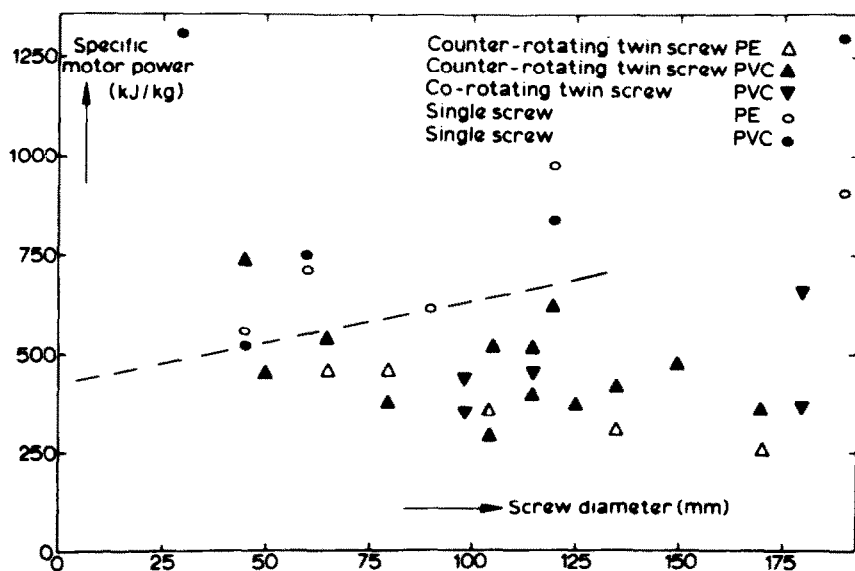


Fig. 15. Specific power consumption, kJ kg^{-1} .

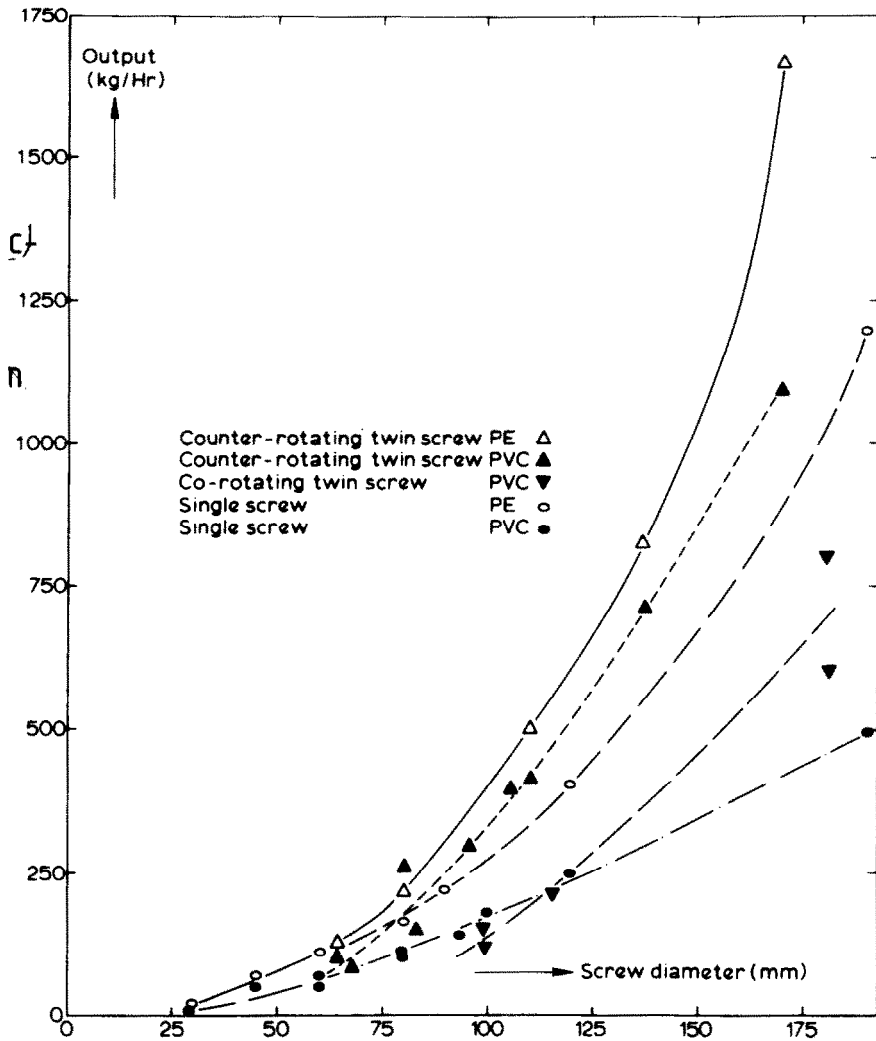


Fig. 16. Throughput as a function of screw diameter for single- and twin-screw extruders for 1962 and 1978.

AN ENGINEERING ANALYSIS

From the foregoing it will be clear that it is not easy to compare commercially-available twin- and single-screw extruders, although the screw diameter can provide a basis for this.

Unfortunately, not enough data are available on different kinds of food extruders to make a reliable and useful comparison. However, from our own experiments we have found enough similarities between the extrusion of some biopolymers and some synthetic polymers to justify a comparison with plastic machinery. Figure 14 compares the maximum output as specified by a number of machine manufacturers in 1962 and 1978 for single-screw and various types of twin-screw machines. This insignificant shift in the data between 1962 and 1978 is striking. Although there is a rough similarity between the output-screw diameter relationship for single-screw and twin-screw extruders, it can be seen that twin-screw extruders have in general a higher output than single-screw machines.

However, the t.s.e.'s run at much lower speeds (20–60 rpm) than the s.s.e.'s (100–400 rpm). This means that the effective transportation in twin-screw machines is much greater. The two screws almost double the uptake in the feed section and, moreover, under normal operating conditions there is no back pressure present in the feed zone. Regarding these differences in rotational speed and output, it is interesting to compare the specific motor power (motor power per unit of product) and throughput for the different types of machines (Figs 15 and 16). It can be seen that specific motor power is generally higher for s.s.e.'s than it is for t.s.e.'s. In Figs 17 and 18 the throughputs and specific power consumption are given for maize grits in a conical t.s.e. provided with a screw set suitable for PVC. The influence of die diameter and moisture content is shown in Figs 19 and 20.

It is possible to obtain identical viscograms from a conical t.s.e. and an s.s.e. (see Figs 21 and 22).

One of the specific advantages of t.s.e.'s is clear. An extruder is a thermodynamic unit. Most of the power to drive the screws is converted into heat, but because of losses in the motor unit, the gear system and the bearings, heat produced by viscous dissipation is more expensive than that acquired from simple heaters. The heat supplied through the barrel may even be waste-heat recovered from other equipment. As most polymers are susceptible to thermal degradation, good thermal control is needed. If the amount of heat produced by viscous dissipation is far more than that supplied through the barrel, temperature control by the barrel heating might become difficult so that the screw speed has to be changed. The associated changes in output can be especially troublesome when the extruder is feeding

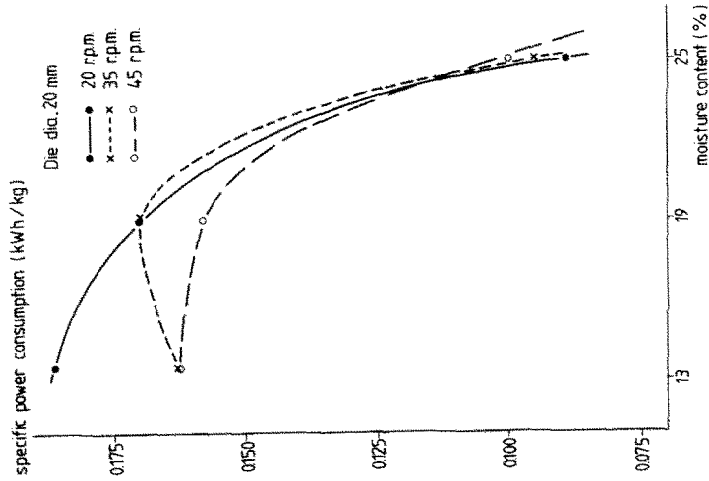


Fig. 18. Specific power consumption versus moisture content in a conical, twin-screw extruder, related to rpm.

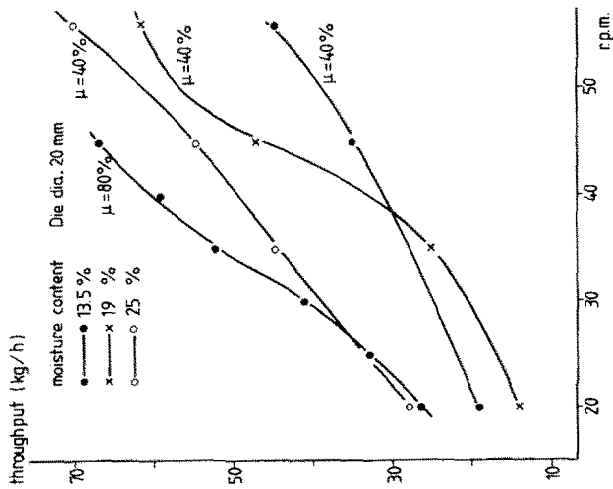


Fig. 17. Throughput related to rpm, moisture content and torque in a conical, twin-screw extruder.

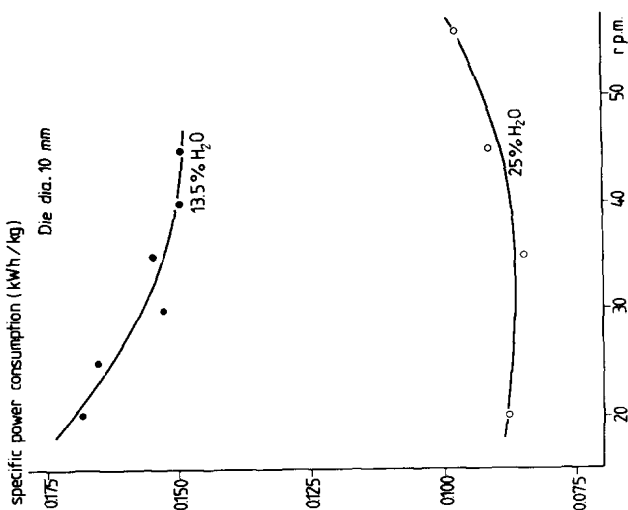


Fig. 20. Specific power consumption versus rpm related to moisture content for one die diameter.

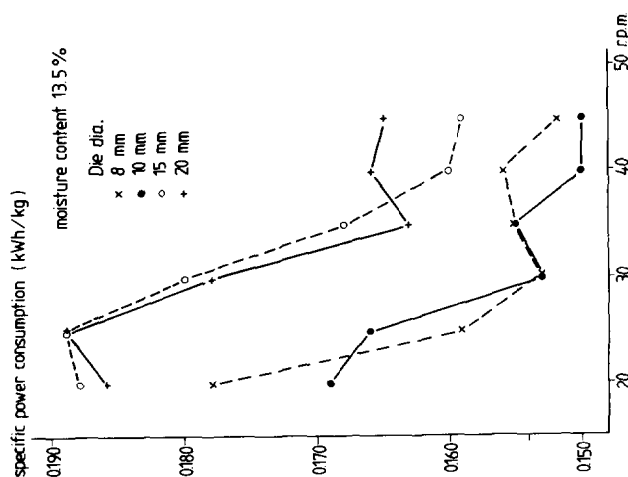


Fig. 19. Specific power consumption versus rpm, related to moisture content and die diameter.

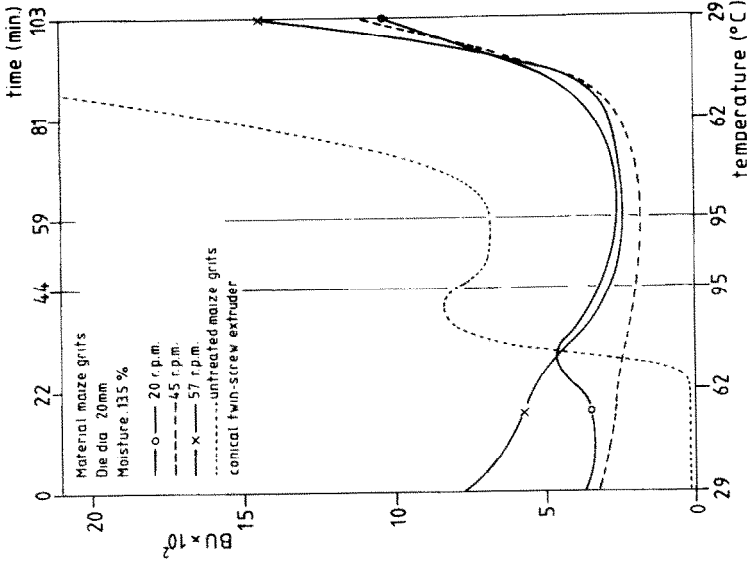


Fig. 21. Brabender viscometer for a single-screw extruder.

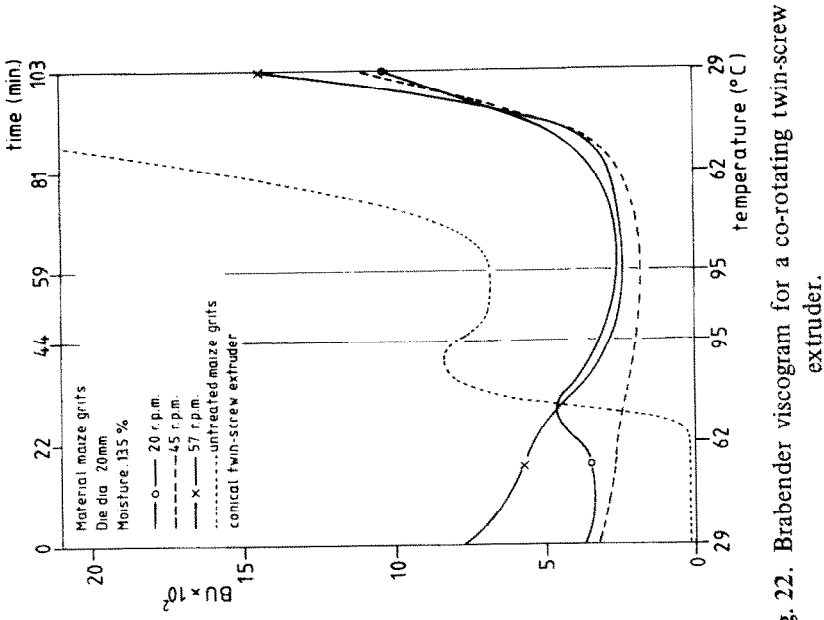


Fig. 22. Brabender viscometer for a co-rotating twin-screw extruder.

other machines. When the viscous dissipation is relatively small and the major part of the heat is supplied externally, as is the case in a t.s.e., then the screw speed and therefore the output can remain constant while the heaters can be used for controlling the process over a wide range of conditions. However, it should be realised that this is at the cost of the shear imposed on the material. The choice of a particular extruder type must be made by a judicious balance between shear requirements and other factors.

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